Two Types of Key-Compromise Impersonation Attacks against One-Pass Key Establishment Protocols

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Abstract. Key establishment protocols are among the most important security mechanisms via which two or more parties can encrypt their communications over an insecure network. This paper is concerned with the vulnerability of one-pass two-party key establishment protocols to key-compromise impersonation (K-CI) attacks. The latter may occur once an adversary has obtained the long-term private key of an honest party, and represent a serious — but often underestimated — threat, because a successful impersonation attack may result in far greater harm than the reading of past and future conversations. Our aim is to describe two main classes of K-CI attacks that can be mounted against all of the best-known one-pass protocols, including MQV and HMQV. We show that one of the attacks described can be somewhat avoided (though not completely eliminated) through the combined use of digital signatures and time-stamps; however, there still remains a class of K-CI threats for which there is no obvious solution.

Keywords: Two-party key establishment, one-pass protocols, key- compromise impersonation, one-way channel.

1 Introduction

In order for two parties to communicate securely over a public network, they must be able to authenticate one another and agree on a secret encryption key. To accomplish this, key establishment protocols are used at the start of a communication session in order to verify the parties' identities and establish a common session key. There are two basic categories of protocols [8]. The first includes so-called *key transport* protocols, in which the session key is created by one entity and is securely transmitted to the other. A second category includes *key agreement* protocols, where information from both entities is used to derive the shared key.

Since the introduction of the Diffie-Hellman key exchange [13], there has been a large number of key establishment protocols proposed, including recent one-round [16,23], two-round [6,24] and three-round approaches [8,10,20]. Some of the disadvantages of these protocols are their high computational and communication cost which, combined with their round complexity, make them unsuitable for use in one-way communication channels. At the same time, there are a variety of applications that require

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low-cost one-way communication. Some of the best-known examples include e-mail and SMS, where the receiver cannot immediately reply, store-and-forward applications (e.g., printers) where messages are sent to resources which need not reply at all, and secure key exchange in mobile environments where low communication cost is critical.

To satisfy these requirements, efficient scalable one-pass two-party key establishment protocols have been developed recently [23,19]. In those schemes, only one of the parties transmits information in order to create the session key (but does not transmit the key itself). This means that one-pass approaches lie somewhere between the key transport and key agreement categories[1]. Furthermore, most, if not all, have been derived from modifications of pre-existing x-round protocols.

Almost all one-pass approaches belong to the category of authenticated key establishment (AK) protocols, because they provide *implicit key authentication* (IKA), meaning that the two (uncorrupted) parties using the protocol are assured that no one else can possibly learn the value of their session key. On the other hand, one-pass protocols cannot achieve *known key security* (K-KS) because an adversary can simply replay a previous protocol run that he has managed to record; nor can they provide *perfect forward secrecy* (PFS) because when long-term private keys are compromised, previous session keys are no longer secret. It is known that there can be no protocol for implicit authentication that achieves PFS with two or fewer messages [19]. The lack of *key control* is another drawback of one-pass protocols; only one entity sends information to the other, so it is possible for the sender to choose or influence the value of the session key. Finally, one-pass approaches are prone to *key-compromise impersonation* (K-CI) attacks, in a number of ways which will be discussed shortly.

Arguably, protocol designers are often more concerned with PFS, and seem to ignore K-CI [30]. However, K-CI can potentially have more serious consequences: besides reading past or future conversations, an attacker would also be able to elicit additional information that may never have been communicated otherwise, by masquerading as a different honest principal. Because of this, it is our opinion that more emphasis should be given on a protocol being K-CI–resistant. In this paper, we discuss and demonstrate a series of impersonation attacks that affect one-pass key establishment protocols, after key-compromise has occurred. We also examine the use of time-stamps and standard digital signatures for the purpose of withstanding two certain K-CI attacks. To the best of our knowledge, this work, and its abreviated version in [11], are the first detailed studies of such attacks on one-pass key establishment protocols.

The remainder of this paper is organized as follows: In Section 2 we fix notation and review some required definitions. Section 3 describes some of the best known one-pass two-party key establishment protocols. Section 4 discusses the K-CI vulnerability vis-a-vis a series of important and widely-used applications, and describes two basic types of K-CI attacks and possible responses.

[1] For this reason, it seems more appropriate to speak of one-pass *key establishment* as opposed to *key agreement*, as is done in most of the literature.

2 Notation and Primitives

The protocols described in the next section can be defined over any finite commutative group $\mathbb{G}$ of order n that comes equipped with a "difficult" discrete logarithm problem. Throughout this paper we consider asymmetric protocols[2] based on elliptic curve cryptosystems (i.e, $\mathbb{G}$ will be the group of points on an elliptic curve), and we will use additive representation for group operations [17]. We will let P denote a generator of $\mathbb{G}$, and will assume that $\mathbb{G}$, P, and n are fixed and known to the parties in advance. We will write cP to denote *integer to point* multiplication, also known as scalar multiplication, where $c \in \mathbb{Z}_n^*$. Finally, we will require the notion of a bilinear pairing over a group of elliptic curve points.

Definition 1. Bilinear Pairings. *Let $\mathbb{G}_1$ be an additive cyclic group of prime order q generated by P, and $\mathbb{G}_2$ be a multiplicative cyclic group of the same order. A map $\hat{e} : \mathbb{G}_1 \times \mathbb{G}_1 \mapsto \mathbb{G}_2$ is called a bilinear pairing if it satisfies the following properties:*

- *Bilinearity: $\hat{e}(aP,bQ) = \hat{e}(bP,aQ) = \hat{e}(abP,Q) = \hat{e}(P,abQ) = \hat{e}(P,Q)^{ab}$ for all $P,Q \in \mathbb{G}_1$, $a,b \in Z_q^*$.*
- *Non-degeneracy: there exist $P,Q \in \mathbb{G}_1$ such that $\hat{e}(P,Q) \neq 1$.*
- *Efficiency: there exists an efficient algorithm to compute the bilinear map.*

All pairing algorithms currently employed in cryptography are based on elliptic curves, and thus make use of Miller's algorithm [27]. Admissible pairings include the Weil, Tate, Ate and η_T pairings [4].

The security of the protocols discussed next is linked to the following problems, whose solution is assumed to be difficult to compute in polynomial time:

Definition 2. Discrete Log Problem (DLP)
Given $P,Q \in \mathbb{G}$, find an integer $a \in \mathbb{Z}_n^*$ such that $Q = aP \in \mathbb{G}$.

Definition 3. Computational Diffie-Hellman Problem (CDHP)
Given $P,aP,bP \in \mathbb{G}$, for some unknown $a,b \in \mathbb{Z}_n^*$, find $abP \in \mathbb{G}$.

Definition 4. Bilinear Diffie-Hellman Problem (BDHP)
Given $P,aP,bP,cP \in \mathbb{G}_1$, for some unknown $a,b,c \in \mathbb{Z}_q^*$, it is difficult to find $\hat{e}(P,P)^{abc}$.

In the following we will apply hash functions and signature schemes to lists of several arguments. In such cases, we are going to write function arguments separated by commas, e.g., $H(X,Y,Z)$. By doing so, we assume that we have a collision-free encoding which maps lists of arguments to binary strings, and that the parties' identities are arbitrary binary strings.

An entity, say Alice, participating in a protocol is assigned a static *key pair* (a,A) which consists of a *public* and a *private key*. Public keys (denoted by upper case letters) are elements of $\mathbb{G}$, while private keys (denoted by the corresponding lower case letters) are elements of $\mathbb{Z}_n^*$. For example, the private key a will correspond to the public key $A = aP$.

[2] A protocol is said to be *asymmetric* if the two entities share only authenticated public information such as a public key with a digital certificate.

Public keys are registered with a trusted directory, called the certificate authority (CA). The CA registers arbitrary keys with the restriction that no party can have more than one public key. We assume that all honest parties have generated their public keys and have registered them with the CA, so that they can be known to and verified by others during protocol execution. Table 1 lists the notation used throughout the paper.

Table 1. Notation

$\hat{A}, \hat{B}$	identities of two communicating parties
P	generator of the group $\mathbb{G}$
n	prime order of $\mathbb{G}$
a, b	static private keys of Alice and Bob, $a, b \in \mathbb{Z}_n^*$
A, B	static public keys of Alice and Bob, $A = aP, B = bP$
r	ephemeral private key
R	ephemeral public key, $R = rP$
sk_i	session key generated by entity i
$\overline{Q}$	denotes the integer obtained from the binary representation of the x-coordinate of an elliptic curve point, Q
H	a plain cryptographic hash function (e.g., SHA-1)
$\bar{H}$	an l-bit hash function, $l = (\lfloor \log_2 n \rfloor + 1)/2$
$\hat{H}$	a special hash function that outputs an elliptic curve point; it is commonly known as *map-to-point* hash function
T	time-stamp
$\hat{e}$	bilinear pairing
$\|\|$	concatenation symbol
$\oplus$	XOR function

3 One-Pass Protocols

In a one-pass AK protocol it is possible for entities Alice and Bob to agree upon a session key after a single message having been sent from Alice to Bob, if Alice has an authenticated copy of Bob's static public key. A two-pass protocol can thus be converted to one-pass simply by replacing Bob's ephemeral public key with his static public key [7]. In this Section we use precisely this technique to create one-pass versions of the following protocols (described in Tables (2 - 9) respectively):

- The Unified Model [1]; it is an AK protocol in the draft standards ANSI X9.42 [2], ANSI X9.63 [3], and IEEE P1363 [15].
- The Key Exchange Algorithm (KEA) designed by the National Security Agency and declassified in 1998 [28]. KEA is the key agreement protocol in the FORTEZZA suite of cryptographic algorithms designed by NSA in 1994 and it is similar to the Goss [14] and MTI/A0 [25] protocols.
- The KEA+ protocol proposed by [22]; a modified version of the KEA protocol, which satisfies stronger security requirements than simple KEA for authenticated key-exchange.

- The MQV protocol [23] that is in the draft standards ANSI X9.42 [2], ANSI X9.63 [3], and IEEE P1363 [15]. MQV was proposed by NSA as the standard key exchange protocol for the US government.
- The HMQV protocol by [19,26] that was proposed as an alternative of MQV. There are two one-pass variants, HMQV(1) and HMQV(2), which are quite similar to one another. HMQV(2) was proposed mainly for reasons having to do with compatibility with the other x-round variants of HMQV.
- The CMQV protocol ("combined" MQV) [31], incorporates design principles from MQV, HMQV and NAXOS [21] protocols.
- The CHHSA protocol was proposed in [12] as a provably secure one-pass two-party key establishment scheme. Among the protocols discussed here, it is the strongest against the general key-compromise impersonation attack which will be described in the next section.

For each protocol, we assume that two entities, say Alice and Bob, each own a static key pair, the public part of which is presumed to be known and verified by the other party. Alice generates an ephemeral key pair (r,R) and sends the ephemeral public key, R, to Bob, along with her identity $\hat{A}$. This ephemeral public key is used only for the duration of the protocol and then destroyed together with the corresponding private key. Afterward, they compute a session key which can be shown to be the same for both of them.

Table 2. One-pass UM

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*,\ R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = aB \| rB$		$sk_B = bA \| bR$

Table 3. One-pass KEA

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*,\ R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = aB \oplus rB$		$sk_B = bA \oplus bR$

Table 4. One-pass KEA+

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*,\ R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = H(aB, rB, \hat{A}, \hat{B})$		$sk_B = H(bA, bR, \hat{A}, \hat{B})$

Table 5. One-pass MQV

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*,\ R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = (r+\overline{R}a)(1+\overline{B})B$		$sk_B = (b+\overline{B}b)(R+\overline{R}A)$

Table 6. One-pass HMQV(1)

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*,\ R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = (r+ad)B$		$sk_B = (bR+bdA)$
where $d = \bar{H}(R,(\hat{A},\hat{B}))$		

4 Key-Compromise Impersonation Attacks

Clearly, if a private key is compromised then the attacker can impersonate the "corrupted" party to other entities, because entities are identified precisely by their private key. This kind of impersonation attack cannot be prevented in any of the existing public key cryptographic schemes. Instead, by "resistance to key-compromise impersonation (K-CI) attacks", we will understand the property of a protocol whereby if one party's long-term private key is somehow disclosed to an adversary, then that adversary will not be able to impersonate *other entities* to that party [7]. A number of security models for K-CI resilience of AKE protocols have been developed in the literature [32,19,21]. The work in [19] mentions, without elaborating, that protocols which use long-term static Diffie-Hellman keys, g^a, g^b, to derive a session key, g^{ab}, are insecure against K-CI attacks. This is the case for all of the one-pass protocols examined here. Before describing the attacks, we review some of the applications for which the use of one-pass protocols has been proposed [29], together with the consequences of a K-CI attack in each setting.

4.1 Consequences of K-CI Vulnerability

The major concern with K-CI is that an adversary can possibly gain much more knowledge than by simply having access to past or future conversations of an entity. Obviously, with knowledge of a party's private key, an attacker can eavesdrop and decrypt past or future conversations of that party[3]. Besides eavesdropping, however, a KC-I attacker would also be able to actively probe for additional information that may never have been communicated otherwise, by pretending to be a trusted entity to the victim (e.g., the attacker steals one's private key and then pretends to be their lawyer or business associate).

Additionally, a successful impersonation attack, could cause the victim to accept harmful content (e.g., viruses, trojans and spywares) from a malicious user that feigns

[3] This attack can be prevented by modern x-round protocols, in which both parties exchange an ephemeral public key.

Table 7. One-pass HMQV(2)

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*$, $R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_A = (1+e)(r+da)B$		$sk_B = (R+dA)(b+be)$
where $d = \bar{H}(R,\hat{B})$ and $e = \bar{H}(B,\hat{A})$		

Table 8. One-pass CMQV

Alice (a,A)		Bob (b,B)
$\bar{r} \xleftarrow{R} \mathbb{Z}_n^*$, $r = \bar{H}(\bar{r},a)$, $R = rP$		
$s = rB + daB$, destroy r	$\xrightarrow{R,\hat{A},\hat{B}}$	
		$s = (R+dA)b$
where $d = \bar{H}(R,\hat{A},\hat{B})$ and $sk_A = sk_B = H(s,X,B,\hat{A},\hat{B})$		

another identity or to accept false information (e.g., the attacker modifies a bank account number, leading the victim to deposit money to a 'wrong' bank account).

E-mail. In an e-mail system one may wish to send encrypted messages by only using their own public information, such as name or e-mail address. Because one party may be temporarily off-line, e-mail communication resembles a one-way channel, and thus an one-pass AK protocol might be suitable in order to send a message without additional communication overload [23,29]. All modern one-pass schemes provide assurance that no user other than the receiver will be able to compute the value of the shared secret key, as long as users remain uncorrupted. However, the vast number of e-mail users combined with the extensive presence of malicious software, makes it likely that private keys stored on personal computers (e.g., in conventional memory) can be compromised. Examples of serious K-CI consequences include the impersonation of a government entity or victim's lawyer to obtain information, and the impersonation of a stockbroker's clients and vice-versa.

E-Commerce. For online transactions, one needs a key agreement protocol that offers authentication of the sender's identity. Furthermore, because the session key must be changed in every session, a protocol must provide both implicit key authentication and key freshness. One-pass AK protocols meet both of these requirements, and have been proposed as a possible mechanism for secure e-shopping [29]. The consequences of a K-CI attack on an on-line transaction might include an adversary, say Eve, impersonating an on-line shop to a client whose private key she has obtained, and asking for personal or credit information.

Mobile and Satellite Transactions. In wireless communications, the authentication of a user is a very important issue, since their physical location may change frequently. At the same time, the computational power of a mobile device is likely to be limited. In light of these considerations, one-pass AK protocols have been proposed as a possible solution in wireless environments, because of their low communication overhead [29].

Table 9. One-pass CHHSA

Alice (a,A)		Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*, R_1 = rP, R_2 = rB$		
$Y = aD$	$\xrightarrow{R_1,Y,T,\hat{A}}$	
		$R_2 = bR_1$
		verifies $\hat{e}(A,D) \stackrel{?}{=} \hat{e}(P,Y)$
$sk_A = H(R_2 \| \hat{A} \| \hat{B} \| T)$		$sk_B = H(R_2 \| \hat{A} \| \hat{B} \| T)$
where $D = \hat{H}(R_2 \| \hat{A} \| \hat{B} \| T)$		

As with K-CI attacks on e-commerce applications, here an adversary can elicit the disclosure of confidential data from the victim(s). Moreover, in cases where the attacker impersonates the wireless connection server, victims may be connected on an unauthorized network, resulting in their mobile device being corrupted further. In a similar way, K-CI attacks can be harmful in one-way satellite communications, such as satellite TV, where clients are not equipped with a transmitter and thus have no alternative to one-pass key establishment.

4.2 K-CI Attacks

We will distinguish between two types of K-CI attacks, defined below.

Type-1. All existing one-pass AK establishment protocols, excluding the one in [12], are open to the general K-CI attack in which an intruder, Eve, masquerades as a different entity and tries to establish a valid session key with the compromised party, Bob. There is no need for eavesdropping in this case: Eve, knowing Bob's private key, can initiate a new session with him by creating and sending an ephemeral public key, R, pretending to be another honest entity, Alice. In that case, Eve can compute the same session key as Bob, who is convinced that the key is shared with Alice. The attack is illustrated in Table 10. Its success is based on the fact that the majority of the one-pass approaches mentioned here do not include a sender verification mechanism. For instance, the exponential challenge-response (XCR) signature (from a player Alice to a player Bob), used in the HMQV protocol [19], can also be constructed by anyone who has knowledge of the recipient's private key. This means that if an attacker has knowledge of Bob's private key, he is able to create a signature of this type and thus impersonate Alice to Bob.

A possible solution to the Type-1 K-CI attack is to have the sender transmit their digital signature on their ephemeral public key (see Table 11). Then, the receiver can verify the signature before accepting the key (and the sender's identity). We stress the importance of including the recipient's identity, $\hat{B}$, in the signed message to avoid the possibility of an attacker impersonating Alice by re-using her signature from a protocol run between Alice and a different entity. The procedure described above does not protect against replay attacks. One way to reduce, but not eliminate, the replay vulnerability, is to have parties append time-stamps to their messages[4]. More specifically, Bob can

[4] We note that the proposed technique for improving K-CI security in HMQV can be made more efficient by computing d as $\bar{H}(R,(\hat{A},\hat{B}),T)$ and signing only the d value.)

Table 10. Type-1 K-CI attack on HMQV(1)

Eve knows b, B, A		Bob (b, B)
$r \xleftarrow{R} \mathbb{Z}_n^*$, $R = rP$	$\xrightarrow{R,\hat{A}}$	
$sk_E = (bR + bdA)$		$sk_B = (bR + bdA)$
where $d = \bar{H}(R, (\hat{A}, \hat{B}))$		

Table 11. Solution to Type-1 K-CI attack on HMQV(1)

Alice (a, A)		Bob (b, B)
$r \xleftarrow{R} \mathbb{Z}_n^*$, $R = rP$	$\xrightarrow{R,\hat{A},T,Sig_{\hat{A}}(R,T,\hat{B})}$	
		verify $Sig_{\hat{A}}(R, T, \hat{B})$
		if OK continue
$sk_A = (r + ad)B$		$sk_B = (bR + bdA)$
where $d = \bar{H}(R, (\hat{A}, \hat{B}))$		

examine the time-stamp T sent by the protocol initiator, Alice, and terminate the protocol if "too much" time has elapsed since T. Of course, this requires synchronization of Alice's and Bob's clocks, to within some reasonable tolerance. Depending on the statistics of the transmission delay imposed by the communication channel, an entity can set a time threshold that leaves a potential attacker little time to mount a replay attack. If Alice's and Bob's clocks are perfectly synchronized and the transmission delay is known with certainty, then the time left for an attack could be made arbitrarily small. The question of what is an acceptable time threshold will generally be application-dependent, and will not be discussed further here. Finally, one could also claim that signing every message involving the shared key could be a possible solution to Type-1 K-CI attacks, however, the additional communication/computational cost would be very high.

Remark. We have not included here a formal proof of security against Type-1 K-CI attacks for the fix proposed in this section. Such proof could be constructed based on the model of [32], where in addition to the typical queries an adversary can make, one introduces a new query called *key compromise*. When an adversary issues this query for a specified party, Bob, the adversary learns Bob's long-term secret, b, but no other internal information. Because in our case there is but a single data flow, one can easily show that a successful Type-1 K-CI attack against the protocol in Table 11, for example, implies that the adversary has defeated the digital signature scheme under the assumptions made on the time-stamps T.

Type-2. There is a special K-CI attack that apparently succeeds with *all* one-flow protocols. It is illustrated in Table 12. An intruder, Eve, that learns Bob's secret key and then eavesdrops on a single message from Alice (the initiator of the protocol) to Bob, would then be able to compute the current session key and thus impersonate Alice (but *no one else*) to Bob, and only for the current session. To achieve this, after Eve intercepts Alice's ephemeral public key, R, she computes the session key in the same way as Bob, and then must "cut out" Alice from the current conversation. There is no apparent solution for this

Table 12. Type-2 K-CI attack on HMQV(1)

Alice (a,A)	Eve knows b,B,A	Bob (b,B)
$r \xleftarrow{R} \mathbb{Z}_n^*$, $R = rP$		
	$\xrightarrow{R,\hat{A},T,Sig_{\hat{A}}(R,T,\hat{B})}$ - - - - - - - - - $\rightarrow$ $\xrightarrow{R,\hat{A},T,Sig_{\hat{A}}(R,T,\hat{B})}$	
		verify $Sig_{\hat{A}}(R,T,\hat{B})$
	intercept Alice	
	$sk_E = (bR + bdA)$	$sk_B = (bR + bdA)$
	where $d = \bar{H}(R,(\hat{A},\hat{B}))$	

attack, even if a scheme is to be equipped with digital signatures or time-stamps, or both. However, the Type-2 attack is rather limited in scope compared with the general K-CI attack in which the intruder can impersonate *any* entity and at *any* time.

5 Conclusions

In this paper we have examined the resistance of the most efficient one-pass asymmetric AK establishment protocols to K-CI attacks. The use of one-pass protocols may be unavoidable in settings where the communication channel is one-way (e.g., e-mail, store-and-forward applications) or in cases where computational and communication cost is to be minimized (e.g., low-power mobile applications). We distinguished between two types of K-CI threats, to which almost all of the protocols examined here are vulnerable. The only approach that resists Type-1 KC-I attacks (via the technique proposed in this paper) is CHSSA [12]. However, the use of bilinear pairings in [12], makes that protocol less efficient compared to the others examined here. Security against Type-1 K-CI attacks can be somewhat improved with the help of standard digital signatures and time-stamps, at a significant additional communication and computational cost. An open task in this area is to design an one-pass key establishment protocol based on the CDH problem, using a non-pairing based short digital signature scheme.

Although forward secrecy (also related to party corruption) is usually considered more important than K-CI, our discussion suggests that a K-CI attack can be more dangerous: in widely-used applications, such as e-mail, mobile and e-business transactions, the security practices of the average user are likely to be lax (making key-compromise a real possibility) thus giving a K-CI adversary the chance to ask for and obtain information that would have not been transmitted otherwise. For this reason, the use of one-pass protocols should be avoided when possible.

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